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Summary

We list the materials that are anticipated to be placed into the Linac Coherent Light Source (LCLS) x-ray free electron laser (XFEL) beam line, their positions, and the absorbed dose, and compare this dose with anticipated damage thresholds.

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Introduction

There is great concern that the short, intense XFEL pulse of the LCLS will damage the optics that will be placed into the beam. We have analyzed the extent of the problem by considering the anticipated materials and position of the optical components in the beam path, calculated the absorbed dose as a function of photon energy, and compared these doses with the expected doses required (i) to observe rapid degradation due to thermal fatigue, (ii) to reach the melting temperature, or (iii) to actually melt the material.

Model Description

We model the FEL beam as a Gaussian beam that has a plane phase front at the plane $z = z_0$ inside of the undulator as described in Ref. [1]. The XFEL saturated power was assumed to be 10 GW, the length of the pulse to be 233 fs, and the electron beam width at z_0 to be 31 μm. The x-ray dose incident on the materials is generally a function of the distance z and the photon energy E_{phot} (827 to 8267 eV). The absorbed dose was calculated from tabulated absorption cross sections [2]. For each material and distance *z*, we calculated the absorbed dose as a function of E_{phot}, and took the maximum with respect to E_{phot} as the *maximum absorbed dose.*

The absorbed dose required to reach the melting temperature was calculated considering the temperature-dependent heat capacity of the materials [3]. For yttrium-aluminum-garnet (YAG) we used data from Ref. [4], and for lutetium orthosilicate (LSO) we used data for Mg_2SiO_4 instead since appropriate data for Lu_2SiO_5 was not available. The absorbed dose required to actually melt the materials was calculated by considering the heat of fusion if data was available [4].

The maximum temperature rise δT beyond which the onset of a rapid degradation by thermal fatigue is given by [5]

$$\delta \mathrm{T} = \frac{3(1-\upsilon)\mathrm{G}}{\alpha \mathrm{E}},$$

where ν is the Poisson ratio, G is the yield strength, E is the Young's modulus, and α the volumetric thermal expansion coefficient. From δT and the heat capacity the corresponding dose can be calculated.

Results

Table I shows the optical components in the XFEL beam, their position in the beam path [6], the material that is exposed to the beam, and the x-ray angle of incidence. Table II shows the melting temperatures T_{melt} of the materials, and the absorbed doses required to reach T_{melt}. Also shown in Table II is the absorbed dose required to completely melt the material and the doses for onset of damage by thermal fatigue [5]. The data for LSO in this table is only approximate or missing since the heat capacity and various thermo-mechanical properties are unknown.

The maximum absorbed dose as a function of distance *z* for the different materials is shown in Figure 1. Also indicated are the positions of some optical elements. At the worst-case photon energy, the Si layer in the total energy calorimeter will reach T_{melt} but there is not enough energy for full melting. The YAG crystal in the WFOV direct imager will absorb just enough energy to reach T_{melt}. If an LSO crystal is used in the WFOV direct imager instead, it will absorb energy in excess of the dose required to reach T_{melt}. The temperatures of the other materials are expected to stay below T_{melt}. Figure 2 shows the absorbed dose for the different materials as a function of E_{phot} in the plane of the diagnostic package. For most photon energies E_{phot} all materials exceed the dose for onset of damage by thermal fatigue during multiple exposures. At E_{phot} = 8267eV only SiC is expected not to get damaged during multiple exposures.

References

[1] R. Bionta, "Controlling dose to low Z solids at LCLS", *LCLS-TN-00-3*.

[2] B.L. Henke, E.M. Gullikson, and J.C. Davis, "X-ray interactions: photoabsorption, scattering, transmission, and reflection at E=50-30000 eV, Z=1-92", *Atom. Data Nucl. Data Tab.* **54**, 181 (1993).

[3] NIST Standard Reference Database Number 69, June 2005 Release.

[4] R.J.M. Konings, R.R. van der Laan, A.C.G. van Genderen, and J.C. van Miltenburg, "The heat capacity of Y3Al5O12 from 0 to 900 K", *Thermoch. Acta* **313**, 201 (1998).

[5] D.D. Ryutov, Rev. Sci. Instr. **74**, 3722 (2003).

[6] K. Wong, *private communication.*

Component	z (LCLS)	z	material	angle of incidence
	(m)	(m)		
Undulator Exit	646.5	0.0	N/A	N/A
PPS 1			possibly Be or B_4C	normal
Slit A	710.2	63.7	B_4C/Ta/B_4C	normal
PPS 2	717.4	70.9	possibly Be or B_4C	normal
Solid Attenuator	736.6	90.1	Be	normal
WFOV Direct Imager	740.7	94.2	YAG ($Y_3Al_5O_{12}$)	normal
	740.7	94.2	LSO (Lu_2SiO_5)	normal
Total Energy Calorimeter	740.7	94.2	Si	normal
Indirect Imager	740.7	94.2	SiC/B_4C	
Slit B	742.0	95.5	B_4C/Ta/B_4C	normal
Mirror 1 (Offset Mirror)	743.9	97.4	SiC	1.5mrad
Mirror 3,4 (Offset Mirror)	747.9	101.4	Be	15mrad

Table 1: Position, exposed material, and photon angle of incidence for the optical components.

Material	T_{melt} (C)	Dose to reach T_{melt} (eV/atom)	Melting dose (eV/atom)	Dose for thermal fatique (eV/atom)
B_4C	2450	0.63	0.74	0.02
Be	1289	0.34	0.51	0.09
LSO	2050	~ 1.0 (*)		
Si	1414	0.38	0.88	0.07
SiC	2545	0.65	1.03	0.06
YAG	1970	0.51		0.02

(*) based on thermal properties of Mg2(SiO5)

Table 2: Melting temperatures T_{melt}, doses to reach T_{melt} (D_1) and to completely melt the material (D_2), respectively, and doses for onset of damage by thermal fatigue (D_3) for the different materials used in x-ray optics.

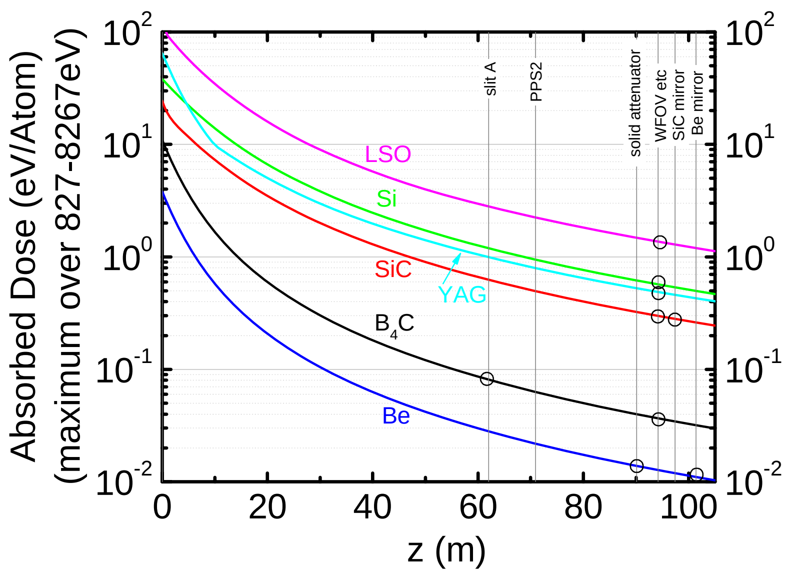

Figure 1: Maximum absorbed dose for different materials along the XFEL beam, taken as the maximum absorbed dose over the XFEL energy range (827 to 8267eV), and assuming a normal angle of incidence. Overlaid are the positions of some optical elements.

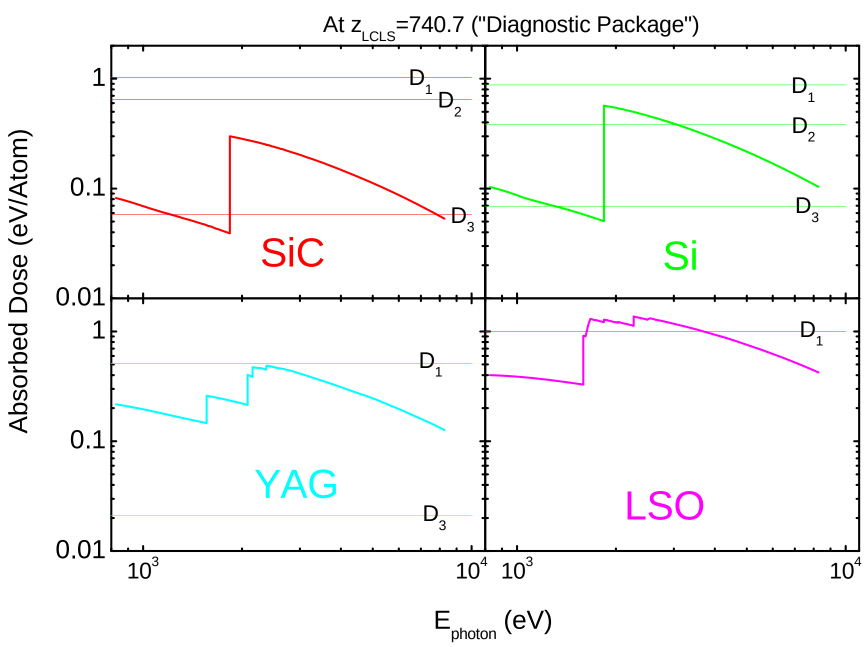

Figure 2: Absorbed dose for different materials in the plane of the diagnostic package (containing for example the WFOV direct imager and the total energy monitor) as a function of photon energy E_{phot}. As far as data was available, also indicated are the absorbed doses required to reach T_{melt} (D_1), the doses required to actually melt the material (D_2), and the doses for onset of damage by thermal fatigue (D_3).